

NON-THERMAL PHENOMENA IN GALAXY CLUSTERS

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The recent evidences of the presence of magnetic fields and relativistic particles in galaxy clusters are reviewed. The existence of μG -level magnetic fields in cluster atmospheres appears well established from the detection of diffuse radio emission and from studies of Rotation Measure. The fact that the diffuse radio emission is not common in clusters favours the hypothesis that the population of relativistic particles, produced during the cluster formation by AGNs or star formation, are reaccelerated by recent cluster merger processes.

1. Introduction

It is nowadays well established that the clusters of galaxies contain two relevant non-thermal components: magnetic fields and relativistic particles.

The most detailed evidence for these components comes from the radio observations. A number of clusters of galaxies is known to contain large-scale diffuse radio sources (radio halos and relics) which have no obvious connection with the cluster galaxies, but are rather associated with the intracluster medium (ICM). The synchrotron origin of the emission from these sources requires a population of GeV relativistic electrons and cluster-wide μG magnetic fields in the ICM.

Indirect evidence of the existence of cluster magnetic fields derives from studies of the Rotation Measure of radio galaxies embedded within the cluster thermal atmospheres or located behind them. Probe of the existence of a population of relativistic particles is obtained from the detection of non-thermal emission of inverse Compton origin in the hard X-ray (HXR) and extreme ultraviolet (EUV) domains.

The intrinsic parameters quoted in this paper are computed with a Hubble constant $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and a deceleration parameter $q_0 = 0.5$.

2. Radio halos, relics and mini-halos

Great attention has been devoted in recent years to the study of cluster large-scale diffuse radio sources. New halo and relic candidates were found from searches in the NRAO VLA Sky Survey³⁰, in the Westerbork Northern Sky Survey⁴⁰ and in the survey of the Shapley Concentration⁶⁰. The number of clusters with halos and relics is presently around 50. Their properties have been recently reviewed by Giovannini and Feretti³³.

Radio *halos* are diffuse radio sources of low surface brightness ($\sim \mu\text{Jy arcsec}^{-2}$ at 1.4 GHz) and approximately regular shape, similar to the diffuse source Coma C at the center of the Coma cluster, first classified by Willson⁶¹. They are typically extended $\gtrsim 1$ Mpc (although smaller halos down to $\lesssim 500$ kpc in size have also been detected), are unpolarized and show a steep radio spectrum typical of aged radio sources ($\alpha \gtrsim 1$). The spectrum of Coma C shows a radial decrease²⁹ from $\alpha \sim 0.8$ at the cluster center, to $\alpha \sim 1.8$ beyond a distance of about $10'$.

Recently, radio halos have been studied in distant clusters, as A665³¹ ($z = 0.1818$), A2163²³ ($z = 0.203$), A2744³⁶ ($z = 0.308$), and CL 0016+16³¹ ($z = 0.5545$). A powerful radio halo was found in the hottest known cluster of galaxies 1E0657 – 56⁴¹ ($kT = 15.6$ keV; $z = 0.296$). The existence of a complex halo and a possible relic has been confirmed in A754^{39,1}, where the presence of diffuse emission was debated in the literature.

A possibly related phenomenon to radio halos is a class of sources found in the cluster peripheral regions, the *radio relics*. Relic sources are similar to halos in their low surface brightness, large size and steep spectrum. Unlike halos, they generally show an elongated structure and are highly polarized. The prototype of this class is 1253+275, in the Coma cluster, first classified by Ballarati et al.³. A spectacular example of two almost symmetric relics in the same cluster is found in A3667⁵³. A puzzling relic source is 0917+75^{37,31}, located at 5 to 8 Mpc from the centers of the closest clusters (A762, A786, A787), thus not unambiguously associated with any of them.

Feretti²¹ argued that halos and relics are not the same objects seen in projection, i.e. halos are really at the cluster center and not simply projected onto it. Halos and relics may indeed have different physical origins (see Sect. 6).

Mini-halos are diffuse radio sources of moderate size (~ 500 kpc) surrounding a dominant powerful radio galaxy at the center of cooling flow clusters, as detected in the Perseus and Virgo clusters. From a study of the

Perseus mini-halo³⁴, it was argued that a connection between the central radio galaxy and the mini-halo in terms of particle diffusion or buoyancy is not possible. This lead to the suggestion that the relativistic electrons are reaccelerated by turbulence in the cooling flow region of the ICM. Deeper studies of a large sample of mini-halos are needed to clarify the connection between the central radio galaxy and the formation of mini-halos.

2.1. *Physical conditions*

The physical parameters in radio sources can be estimated assuming a minimum energy configuration for the summed energy in relativistic particles and magnetic fields. This roughly corresponds to energy equipartition between fields and particles. The derived minimum energy densities in halos and relics are of the order of 10^{-14} - 10^{-13} erg cm⁻³, i.e. much lower than the energy density in the thermal gas. These calculations typically assume equal energy in relativistic protons and electrons, a volume filling factor of 1, a low frequency cut-off of 10 MHz, and a high frequency cut-off of 10 GHz. The corresponding equipartition magnetic field strengths range from 0.1 to 1 μ G.

Due to synchrotron and inverse Compton losses, the typical lifetime of the relativistic electrons in the ICM is relatively short ($\sim 10^8$ yr)⁵⁵. The difficulty in explaining radio halos and relics arises from the combination of their large size and the short synchrotron lifetime of relativistic electrons. The expected diffusion velocity of the electron population is of the order of the Alfvén speed (~ 100 km s⁻¹) making it difficult for the electrons to diffuse over a megaparsec-scale region within their radiative lifetime. Thus the relativistic particles need to be reaccelerated by some mechanism, acting with an efficiency comparable to the energy loss processes⁴⁹. We will show in the following that recent cluster mergers are likely to supply energy to the halos and relics.

2.2. *Connection to cluster merger processes*

Unlike the presence of thermal X-ray emission, the presence of diffuse radio emission is not common in clusters of galaxies: in a complete cluster sample, 5% of clusters have a radio halo source and 6% a peripheral relic source³². The detection rate of diffuse radio sources increases with the cluster X-ray luminosity, reaching $\sim 35\%$ in clusters with X-ray luminosity larger than 10^{45} erg s⁻¹ (in the Rosat band 0.1-2.4 keV).

To explain the relative rarity of diffuse sources, it has been argued that

the formation of halos and relics is connected to recent cluster merger events. Indeed, mergers generate shocks, bulk flows, turbulence in the ICM. These processes would provide energy to reaccelerate the radiating particles all around the cluster.

Several evidences favour the hypothesis that clusters with halos and relics are characterized by strong dynamical activity, likely related to merging processes. These clusters indeed show: i) substructures and distortions in the X-ray brightness distribution⁵⁷; ii) temperature gradients⁴⁴; iii) absence of a strong cooling flow²⁰; iv) values of spectroscopic β on average larger than 1^{21} ; v) core radii significantly larger than those of clusters classified as single/primary²¹; vi) large distance from the nearest neighbours⁵⁸; vii) large values of the cluster dipole power ratio¹¹.

High resolution X-ray Chandra data have been recently obtained for several clusters with halos or relics, e.g. A665⁴⁵, A2163⁴⁵, 1E 0657-56⁴⁶, A520⁴⁷, A3667⁴⁷. In all these clusters, temperature gradients and gas shocks are detected, confirming the presence of mergers. Preliminary maps of the radio spectral index between 0.3 and 1.4 GHz in A665 and A2163 (Feretti et al. in preparation) show possible connection to the Chandra temperature maps, indicating a link between halos and cluster mergers.

In conclusion, there seems to be convincing evidence that diffuse sources are preferentially associated with high X-ray luminosity clusters with recent mergers. We are not presently aware of any radio halo or relic in a cluster where the presence of a merger has been clearly excluded. On the other hand, not all merging clusters host a diffuse radio source.

2.3. *Halo radio power vs cluster parameters*

The most powerful radio halos are detected in the clusters with the highest X-ray luminosity. This follows from the correlation found between the diffuse source radio power and the cluster X-ray luminosity^{41,1}. An extrapolation of the above correlation to low radio and X-ray luminosities indicates that clusters with $L_X \lesssim 10^{45} \text{ erg s}^{-1}$ would host halos of power of a few $10^{23} \text{ W Hz}^{-1}$. With a typical size of 1 Mpc, they would have a radio surface brightness lower than current limits obtained in the literature and in the NRAO VLA Sky Survey. Therefore, it is possible that future new generation instruments (LOFAR, SKA) will allow the detection of low brightness/low power large halos in virtually all the merging clusters.

It is worth to remind that the correlation is valid for merging clusters with radio halos, and therefore cannot be generalized to all clusters. Among

the clusters with high X-ray luminosity and no radio halo, there are A478, A576, A2204, A1795, A2029, all well known relaxed clusters with a massive cooling flow.

Since cluster X-ray luminosity and mass are correlated⁵⁰, the correlation between radio power and X-ray luminosity could reflect a dependence of the radio power on the cluster mass. This is indeed the case: a correlation of the type $P_{1.4 \text{ GHz}} \propto M^{2.3}$ is derived for radio halos^{36,24}. This is similar to what expected from simple theoretical considerations. Actually, assuming that roughly the energy released in a merger shock is proportional to the gas density ρ and to the third power of the subcluster velocity v^3 , and that $\rho \propto M$, and $v \propto M^{1/2}$, it is obtained that $\dot{E} \propto M^{5/2}$. This could indicate that the cluster mass may be a crucial parameter in the formation of radio halos¹¹. Since it is likely that massive clusters are the result of several major mergers, we conclude that both past mergers and current mergers are the necessary ingredients for the formation and evolution of radio halos. This scenario may provide a further explanation of the fact that not all clusters showing recent mergers host radio halos.

3. Evidence of cluster magnetic fields

Synchrotron radiation from cosmic radio sources is well known to be linearly polarized. A linearly polarized wave of wavelength λ , traveling from a radio source through a magnetized medium, experiences a phase shift of the left versus right circularly polarized components of the wavefront, leading to a rotation $\Delta\chi$ of the position angle of the polarization, according to the law: $\Delta\chi = \text{RM} \lambda^2$, where RM is the Faraday rotation measure. The RM is related to the electron density, n_e (in 10^{-3} cm^{-3}), and to the magnetic field, \mathbf{B} (in μG), as:

$$\text{RM} = 0.812 \int_0^L n_e \mathbf{B} \cdot d\mathbf{l} \quad \text{radians m}^{-2}$$

where the path length \mathbf{l} is in kpc. The RM values can be derived from multifrequency polarimetric observations of sources within or behind the clusters, by measuring the position angle of the polarized radiation as a function of frequency. They can then be combined with measurements of n_e to estimate the cluster magnetic field along the line of sight.

This kind of studies has been performed on several individual clusters, with or without cooling flows, and on statistical samples (see the review by Carilli and Taylor¹² and references therein). In general, the suggestion

from the data is that magnetic fields in the range of 1-5 μG are common in clusters, regardless of the presence or not of diffuse radio emission. At the center of cooling flow clusters, magnetic field strengths can be larger by about a factor of 2. Another result of the above mentioned studies is that the RM distributions tend to be patchy with coherence lengths of 5-10 kpc, indicating that the magnetic fields are not ordered on cluster (Mpc) scales, but consist of cells with random field orientation.

Thus, in most clusters the fields are not dynamically important, with magnetic pressures much lower than the thermal pressures, but the fields may play a fundamental role in the energy budget of the ICM. The simplest model is a uniform field throughout the cluster. However, possible filaments and flux ropes may be present¹⁶. Also, the value of the magnetic field intensity is likely to decrease with the distance from the cluster center, as in Coma⁸ and in A119¹⁵ (here the field scales as $n_e^{0.9}$).

The ICM magnetic fields could be primordial, or injected from galactic winds, or from active galaxies, or produced in shock waves of the large scale structure formation. The seed fields then need to be amplified to give the fields that we observe at present. The most likely possibility is that the magnetic fields are amplified by turbulence following a cluster merger. Simulations⁵² show that the magnetic field energy increases by greater than a factor 10-20 in localized regions during mergers. It is likely that massive clusters undergo several major mergers during their lifetime and that each successive merger will further amplify the fields. Numerical studies^{14,52} of hierarchical merging of large scale structure including an initial intergalactic field of $\sim 10^{-9}$ G show that a combination of adiabatic compression and non-linear amplification in shocks during cluster mergers may lead to ICM mean fields of the order of $\sim \mu\text{G}$.

4. Relativistic particles from Inverse Compton emission

The relativistic electrons present in the ICM produce inverse Compton (IC) radiation because of scattering with the cosmic background photons. Depending on the electron Lorentz factor γ , this radiation is detected as hard X-ray emission ($\gamma \sim 10^4$) or extreme ultraviolet emission ($\gamma \sim 3 \cdot 10^2$).

4.1. *Hard X-ray Emission (HXR)*

The high energy relativistic electrons, with $\gamma \sim 10^4$, responsible for the radio emission in the ICM, scatter off the cosmic microwave background (CMB), boosting photons from this radiation field to the X-ray and γ -

ray regions. Measurements of this radiation provide additional information that, when combined with results of radio measurements (i.e. the ratio of hard X-ray IC emission to radio synchrotron emission), enables the determination of the electron density and mean magnetic field directly, without the need to invoke equipartition. If the X-ray and radio emissions are produced by the same population of electrons undergoing inverse Compton and synchrotron energy losses, respectively, the main expected features of the X-ray emission are: a) power law spectrum with an index which is related to the radio index; b) X-ray to radio luminosity ratio roughly equal to the ratio between the CMB energy density and the magnetic field energy density.

A significant breakthrough in the measurement of HXR emission was recently obtained owing to the improved sensitivity and wide spectral capabilities of the BeppoSAX and the Rossi X-ray Timing Explorer (RXTE) satellites. Non-thermal hard X-ray emission at energies $\gtrsim 20$ keV has been detected in the Coma cluster^{25,51} and in A2256²⁶. The 20-80 keV flux in Coma is $\sim 2 \cdot 10^{-11}$ erg cm⁻² s⁻¹, which leads to a magnetic field of 0.16 μ G. In A2256, the flux in the same energy range is $\sim 9 \cdot 10^{-12}$ erg cm⁻² s⁻¹. A magnetic field of ~ 0.05 μ G is derived for the northern cluster region, where the radio relic is detected, while a higher field value, ~ 0.5 μ G, could be present at the cluster center, in the region of the radio halo.

A marginal detection has been obtained in A2199³⁸, whereas for the clusters A3667, A119, A2163 and A754, only upper limits to the non-thermal X-ray emission have been derived^{23,27}. A possible detection of localized IC emission associated with the radio relic and with merger shocks has been claimed in A85².

It is worth mentioning here that alternative models have been suggested for the explanation of the hard X-ray tails (e.g. non-thermal bremsstrahlung^{6,13,56}). These were motivated by the discrepancy between the value of the ICM magnetic field derived by the IC model and the value derived from Faraday rotation of polarized radiation (see Sect. 5). However, these models may have serious difficulties as they would require an unrealistic high energy input⁴⁹.

4.2. *Extreme Ultraviolet Emission (EUV)*

The Extreme Ultraviolet Explorer have revealed EUV (0.1 to 0.4 keV) emission in excess of the expected thermal emission in Virgo^{42,4} and Coma^{43,7}. The EUV detections in other clusters (Abell 1795, Abell 2199, Abell 4038,

Abell 4059 and Fornax) remain quite controversial. The EUV emission has luminosities of $\sim 10^{44}$ erg s $^{-1}$ and has spectra which decline rapidly going from the EUV to the X-ray band.

The EUV excess may be interpreted to be of thermal origin, due to a relatively cool ($\sim 10^6$ K) emitting gas. However, at these temperatures gas cooling is particularly efficient, and one would expect the presence of resonance lines which are not detected. Therefore, a non thermal interpretation is favoured, i.e. this emission is more likely due to IC scattering of CMB photons by relativistic electrons. This scenario requires an electron population with energies of ~ 150 MeV ($\gamma \sim 300$). These electrons have a too low energy to produce detectable radio emission. Sarazin⁵⁵ pointed out that these electrons have lifetimes comparable to the Hubble time, and should be present in essentially all clusters. In the Coma cluster, Brunetti et al.⁹ suggested that the electron population injected in the central part of the cluster by the head-tail radio galaxy NGC4869 may account for a large fraction, if not all, of the detected EUV excess.

5. Reconciling magnetic field derived values

The IC estimated cluster magnetic fields are typically 0.2 to 1 μ G (Sect. 4.1). These are consistent with the values obtained from equipartition arguments in radio halos (Sect. 2.1). The fields derived using RM observations are instead an order of magnitude higher (Sect. 3).

Goldsmitth & Rephaeli³⁵ suggested that the IC estimate is typically expected to be lower than the Faraday rotation one, because of the expected spatial profiles of the magnetic field and gas density. More recently, it has been shown that IC models which include the effects of more realistic electron spectra, combined with the expected radial profile of the magnetic field, and anisotropies in the pitch angle distribution of the electrons allow higher values of the ICM magnetic field in better agreement with the Faraday rotation measurements^{8,49}.

For example, if the magnetic field strength has a radial decrease, most of the IC emission will come from the weak field regions in the outer parts of the cluster, while most of the Faraday rotation and synchrotron emission occurs in the strong field regions in the inner parts of the cluster.

Recent modeling by Govoni & Murgia (in preparation) shows that the magnetic field substructure and/or filamentation can lead to significant differences between field estimates obtained from different approaches.

Finally, it has been recently pointed out that in some cases a radio

source could compress the gas and fields in the ICM to produce local RM enhancements, thus leading to overestimates of the derived ICM magnetic field strength⁵⁴.

6. Models for Relativistic Particles

A population of relativistic electrons can account for the radio halos and the HXR and EUV emission in clusters via synchrotron and inverse Compton processes, respectively. Current models have been reviewed by Brunetti¹⁰. The relativistic particles could be injected in the cluster volume from AGN activity (quasars, radio galaxies, etc.), or from star formation in normal galaxies (supernovae, galactic winds, etc). Most of the particle production has occurred in the past and is therefore connected to the dynamical history of the clusters.

This population of *primary electrons* needs to be reaccelerated^{8,49} to compensate the radiative losses. The hypothesis that a recent cluster merger is the most likely process acting in the reacceleration of relativistic particles has been worked out in recent years. In major mergers, hydrodynamical shocks dissipate energies of $\sim 3 \cdot 10^{63}$ erg, which could be partly converted into the acceleration of relativistic electrons^{55,59,48}. The shock acceleration has been recently questioned²⁸. Alternatively, stochastic acceleration by a turbulent ICM seems to be an efficient process^{8,22}. The most likely scenario appears to be an episodic injection-acceleration model, whereby one obtains a time dependent spectrum that for certain phases of its evolution satisfies all the requirements⁴⁹.

Another class of models for the radiating particles in halos involves *secondary electrons*, resulting from inelastic nuclear collisions between the relativistic protons and the thermal ions of the ambient intracluster medium. The protons diffuse on large scales because their energy losses are negligible. They can continuously produce in situ electrons, distributed through the cluster volume^{5,48}. In the framework of secondary electron models, it is difficult to explain the observed association between mergers and radio halos, the spectral index radial steepening found in Coma C and the relatively low number of clusters with halos. Strong γ -ray emission, which should be detected by future γ -ray instruments, is expected to be produced in this case, providing a test of the secondary electron models.

Different models have been suggested for the origin of the relativistic electrons radiating in the radio relics, i.e. located in confined peripheral regions of the clusters. There is increasing evidence that the relics are trac-

ers of shock waves in merger events¹⁷. Active radio galaxies may fill large volumes in the ICM with radio plasma, which becomes rapidly invisible to radio telescopes because of radiation losses of the relativistic electrons. These patches of fossil radio plasma are revived by adiabatic compression in a shock wave produced in the ICM by the flows of cosmological large-scale structure formation^{18,19}.

7. Conclusions

Diffuse radio emission is detected in X-ray luminous, massive clusters showing strong dynamical activity and merger processes. It demonstrates the existence of magnetic fields and relativistic particles in the ICM.

Studies of rotation measure of radio sources within or behind clusters indicate the presence of large scale magnetic fields of the order of $\sim \mu\text{G}$ in the majority of clusters, not only in clusters with halos. These fields are likely to result from the amplification of seed fields during the mergers occurring in the cluster formation process.

The population of relativistic particles produce inverse Compton radiation in HXR and EUV. This emission has been presently detected only in a few clusters. Since the radiating particles have short lifetimes, they need to be continuously reaccelerated.

There is a general consensus that recent merger phenomena would provide the energy for the relativistic electron reacceleration, thus allowing the production of a detectable diffuse radio emission. This emission is also likely related to the cluster dynamical history.

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